Test Results of the MDA Ice Detection System for use with NASA's External Tank

Final Report

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October 2005

Submitted to NASA as part of the NASA/TARDEC Space Act Agreement (SAA)

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
31 OCT 2005	**Final**	**-**

4. TITLE AND SUBTITLE	
Test Results of the MDA Ice Detection system for use with NASA's External Tank	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
T. Meitzler, D. Bryk, E. Sohn, D. Bednarz, E. Bankowski, M. Bienkowski, J. Gillis, K. Lane, J. Vala, J Ragusa	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **RDECOM - TARDEC 6501 E. 11 Mile Road. Warren, MI 48397-5000**	8. PERFORMING ORGANIZATION REPORT NUMBER **15315**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

The original document contains color images.

14. ABSTRACT

As part of a Space Act Agreement between NASA-RSC and TARDEC, an electro-optical system to detect ice and estimate ice thickness on the external tank of the space shuttle was tested in TARDEC's Visual Perception Lab.

15. SUBJECT TERMS

Ice detection, infrared, shuttle external tank

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**42**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Table of Contents

Executive Summary

Background

As part of a Space Act Agreement between NASA-Kennedy Space Center (KSC) and the U.S. Army Tank Automotive Research Development and Engineering Center (TARDEC), members of TARDEC's Visual Perception Lab (VPL) performed a technology search and evaluation of potential electro-optical systems capable of detecting the presence and determining the thickness of ice on Space Transportation System (STS) External Tank (ET) Spray-On-Foam Insulation (SOFI). The SAA and subsequent evaluation activity resulted from discussions between NASA-KSC and the Army following the Columbia Shuttle accident. NASA sought a fresh approach to seemingly intractable ice accumulation and assessment problems that had plagued them since the earliest days of the STS Program. The VPL team, having expertise in imaging sensors, desired to contribute in some way to NASA's Return to Flight planning and accomplishment.

Previous research by VPL investigators, following earlier NASA inquiries, indicated that it might be possible to detect and image ice-covered areas with an infrared (IR) camera. In addition it was realized that methods were needed to detect clear ice (transparent to the naked eye), and to discriminate between ice, frost, and water on ET SOFI surfaces. A technology search followed by members of the VPL resulted in a selection of two electro-optical systems as candidates for further investigation. The VPL comparison of these systems, testing, and analyses was the subject of the first report submitted to NASA-KSC in June 2004. As a result of that report, VPL investigators and NASA engineers determined that a system developed by MacDonald, Dettwiler and Associates Ltd. (MDA - formally known as MDR) of Canada offered the greatest potential to support T-3 hour ice debris team detection and evaluation activities on the launch pad prior to STS launches.

The Step Forward

Because of initial favorable test results and the potential for a possible solution to NASA's ET ice assessment problems, specifications were developed, and a contract was let to MDA for the purchase (with NASA provided funds) of a prototype ice detection system. The new system was to be designed and calibrated for SOFI surfaces. TARDEC purchased this system from MDA, and had it delivered to the VPL for independent testing, evaluation, and quality assurance. Over the period from February 22 – March 17, 2005, the VPL team performed various tests to determine the effectiveness of the system to detect and estimate the presence and thickness of ice on ET SOFI test sample material that was provided by NASA-KSC. After testing, the system was shipped to NASA-KSC for familiarization and use by ice debris team personnel, with the target system delivery date being the Discovery Return to Flight ET cryogenic tanking test.

NASA's initial desire was that the system be capable of detecting ice with a thickness and the diameter of a U. S. quarter (approximately, 1/16 inch thick [0.0625 inch] and one inch in diameter) – in essence the Launch Commit Criteria (LCC) for safe vehicle ascent. In addition, the system was to be passive (without emissions), portable for use by the NASA ice debris detection team on access platforms at T-3 hours, and able to meet launch complex safety requirements (i.e. be explosion proof and within EMI/EMC limits). In reality, due to physical

constraints, the developed and approved specifications for this second generation system were not as stringent as initially envisioned. The minimum one-inch diameter resolution was exceeded at ranges less than 50 feet, and although operational detection of ice thickness is within the 0.0625-inch (1/16 inch) specification, its accuracy was ± 0.02 inches. Also, the MDA system cannot be considered "passive," since it emits a Xenon strobe light (<30 Watts). However, NASA ice debris team personnel did not consider this significant, since Xenon lights are currently used on the launch pad, and they received tentative approval for use of this type of active, low intensity strobe for launch pad operations.

There were several problems identified with the proposed planned solution and contract. They were namely: a) the roughness of the ET foam surface exceeds the LCC thickness specification of no more than 1/16 of an inch, b) the shortness of system development and testing time, and c) the difficulties in test setup (e.g. manual ice thickness measurements for ice thickness verification, ice density measurement, the difficulty in making frost on SOFI, ice/water concurrent testing, and the unknowns of the developed and basically untested system). In spite of these concerns and uncertainties, it was decided by the three parties, that purchase, development, and testing of the MDA proposed system proceed because of the criticality of ET ice detection and measurement, and the importance of STS Return to Flight.

Description of the MDA System

The MDA system uses a low power near-infrared Xenon strobe to illuminate a surface on which there may be ice—in this case, ET SOFI. After illumination of the SOFI surface, electromagnetic energy is reflected back and focused on an IR (1.1 to 1.4 micron) sensor. The sensor (an un-cooled focal plane array) provides inputs to a linked computer. Based on the electromagnetic theory of reflection of light at the surface of a dielectric (ice in this case), the computer estimates the thickness of ice, if present. Various ice thickness ranges are color-coded (e.g., blue = 0.020-0.029 inch, green = 0.030-0.039 inch, yellow = 0.040-0.049 inch, red ≥0.050 inch)[10] on the system monitor to help the operator interpret values quantitatively. A circular "bulls-eye" is shown on the system display to align a small –target area. The average measured ice thickness from pixels located in the bulls-eye (64 pixels 8 x 8), is displayed on-screen in a field labeled "tkns in" (i.e. thickness inches). The system and its components (sensor, VHS recorder, and battery power supply) are contained in N_2 purged enclosures, and are mounted on a two wheeled cart provided by NASA.

Research Questions and Test Results

Four research questions were jointly developed and mutually agreed upon prior to MDA system delivery and test initiation. Goals and descriptions of the test results follow.

Goal 1: Determine whether the MDA system can detect low-density ice (LDI: 18-37 lb/ft^3), and if so, how it compares with the results for normal density ice (NDI).

Observations: NASA scientists have reported that the density of ice buildup on the ET at KSC has been in the range 18-37 lb/ft^3 (i.e. LDI).[2] Normal density ice (NDI), as made in a freezer, is typically about 57 lb/ft^3 (and is not normally formed on the ET during KSC pre-launch

operations). For this goal a SOFI sample was attached to the outside of a metal container, which was filled with liquid Nitrogen (LN2) in order to grow LDI on the SOFI sample. Preliminary attempts proved to only yield frost of density less than 18 lb/ft^3. In subsequent trials using various techniques (enclosure, humidifier, water spray), LDI was attained in two recorded trials.

Conclusion: It was observed that the MDA system detected LDI and frost, although with instability. To compare LDI to NDI measurements, it was thought, that numerical comparisons could be made from later goal testing with NDI. Importantly, it was observed that frost and LDI thickness was considerably underestimated by the MDA system, in comparison with actual physical measurements. Later observations indicated that LDI measurements were also underestimated in comparison to NDI measurements. Therefore, the MDA system was found to be ice density dependent in its estimate of ice thickness. That is, lower ice density seems to cause the MDA system to further underestimate ice thickness when compared to NDI. Thus, there would be risk associated with relying on the MDA system solely for quantitative ice thickness measurements.

Goal 2: Determine if water composition used to make ice has any effect on the MDA system to determine the presence of ice on SOFI, and whether the MDA camera, an infrared-based system, can discern between ice and cold water.

Observations: Three ice/water compositions were tested: distilled water, local Michigan rain water, and tap water. It was evident from the MDA visual display that the system was able to determine the presence of ice on SOFI samples regardless of water composition, and could distinguish cold (47°F) water on SOFI from frozen ice on SOFI. Water appeared as “undefined” (pseudo-colored black) on the MDA system monitor.

Conclusion: Due to the nature of these tests, only qualitative results (and not quantitative data) are presented to answer the Goal 2 objectives. Through visual inspection, the MDA system consistently distinguished between ice and cold water independent of whether the ice and water was from distilled water, Michigan rain water, or tap water. From this qualitative testing, it can be concluded that the composition of test water from different sources did not play a role in detecting water or ice made from the three water types. However, it should be pointed out, that the MDA system cannot discern water from other “undefined” materials (e.g. wood, metal), because it had been calibrated for SOFI ice detection only.

Goal 3: Determine if the MDA system can detect and measure the thickness of ice greater than or less than 0.0625 inch (1/16 inch), and if the estimation of ice thickness is range independent.

Observations: The 0.0625 inch threshold LCC is important (as mentioned earlier) for a “go—no go” launch decision because of the danger of falling ice onto flight crew windows, orbiter thermal tiles, and Reinforced Carbon-Carbon (RCC) wing panels. Also, launch structure access for viewing and sensing ice forming ET areas vary, and for that reason range independence is important. NASA-KSC’s launch pad configuration dictated about a 25 to 75 foot range for T-3 hour ice debris team inspections. For this phase of VPL testing, agreed upon test ranges were 25, 50, 60, and 75 feet.

A precision analog dial indicator gauge was used to verify actual ice thickness. The dial gauge and MDA estimates for ice thickness differed appreciably in these tests. The MDA system was found to be somewhat unstable in its ice thickness estimates, leading to inconsistent data. MDA has stated that some of the noise or instability may be attributed to the long time delay between strobe flashes (three seconds), and spatial fluctuation of the strobe beam pattern that are present in this proof-of-concept version of the system.

Conclusion: Empirical evidence indicates that the MDA system can detect ice less than or greater than 1/16 inch. However, the system showed a lack of consistency in ice thickness measurements. Empirical evidence also indicates that the MDA system is not able to accurately estimate ice thickness independent of range (i.e. as range changes for fixed ice examples, so do the thickness measurements).

Goal 4: Determine the accuracy of the MDA system's ice thickness estimation.

Observations: A dial indicator gauge was used to measure actual ice thickness. As a point of validation, an assumption must be made that ice thickness determination by use of the dial indicator gauge is accurate to some tolerance greater than the MDA system. More specifically, coupled with the dial gauge manufacturer's specifications (± 0.002 inch) and human repeatability (± 0.005 inch), a cumulative inaccuracy of ± 0.007 inch is estimated with the device. The overall uncertainty of the MDA system, as stated by the developer, is ± 0.02 inch.[9] Therefore, measurements for dial gauge use are significantly better than the MDA system.

Later data analysis, however, showed inconsistencies that prompted a reexamination of gauge measurements made on SOFI samples 2B and 3B. Later measurements on sample 2B (without ice) showed differences of 0.03 inches from previous measurements. The origin of these errors is not certain, except to note, that these B samples had irregular bottom surfaces, and therefore may have made an unstable measuring platform.

Conclusions: The system did not have consistent readings even for fixed samples and distances. Inconsistency and inherent noise in the current proof-of-concept system, coupled with melting ice samples, and sample measurement difficulty for samples 2B and 3B, prevented a satisfactory data analysis. Without system modification, and additional testing, it is recommended that the current MDA system be used only as a qualitative, rather than quantitative, ice measurement device useful in locating the presence and relative thickness of ice.

For these reasons, without additional testing, it is recommended that the current MDA system be used as a qualitative, rather than quantitative, ice measurement device to indicate the location and relative thickness of ice.

Conclusions

The present MDA system, as tested in the TARDEC VPL during the February 22 - March 17, 2005 test period is primarily a thin ice detection system that has the potential to qualitatively detect the presence on NASA ET SOFI of: a) low-density ice (18-37 lb/ft^3) common to the KSC launch environment, and b) ice of thickness ≥0.0625 inches (the NASA LCC). The system can

clearly distinguish between areas of SOFI that are covered by cold water versus those areas that are covered with NDI-type ice, and where NDI is present to at least 0.02 inch thick. The system does not appear to be effected by water composition, either for detecting water, or detecting ice made from various sources of water.

However, the present MDA system: a) does not consistently determine ice thickness for target areas in the range measured (25 to 75 feet), b) does not measure linearly in this range, and c) considerably underestimates normal-density and low-density ice/frost thickness, as found on actual ET SOFI surfaces.

The system was also found to be unstable during VPL testing. MDA has stated that some of the instability may have been due to the long time delay between strobe flashes and fluctuation in the strobe beam pattern, both of which MDA claims to have reduced with modifications in a subsequent prototype. The system has sensor range limitations, which are a function of strobe light intensity, sensor efficiency, and target surface reflectance and absorption. Whether, the physics inherent in the MDA system design is the limiting factor, or whether these issues may be resolved in subsequent engineering optics/sensor/software modifications, remains to be proven.

In summary, TARDEC investigators believe that the present proof-of-concept MDA device may be used by the NASA-KSC ice debris team for T-3 hour inspections to indicate areas where ice may be present on ET SOFI, and that may warrant further human inspection. At this stage of the MDA system's development, it is not recommended the system be relied on as the sole indicator of ice thickness, or ice presence.

Future Work

It is suggested by TARDEC investigators that more extensive tests be done on the current proof-of-concept system, or its successor, to determine precision and accuracy in estimating ice thickness under environmental conditions similar to those at KSC. MDA has expressed interest in pursuing development of an operational system that would meet the needs of the ice debris inspection team.

Future suggested modifications to the MDA system to make it more useful would include the following:

1. Greater stability and linearity in ice thickness estimates.
2. Ability to maneuver the bulls-eye in software (e.g. cursor).
3. Capability of imaging at closer and further distances (possible zoom).
4. Higher resolution focal plane array.
5. Digital recording (disk, DVD).

Test Results of the MDA Ice Detection System for use with NASA's External Tank

Final Report

Introduction

This test report has been prepared as part of a Space Act Agreement (SAA) signed on 21 Jan. 2004 by the National Aeronautics Space Agency (NASA)-Kennedy Space Center (KSC), of Florida and the U.S. Army Tank Automotive Research, Development & Engineering Center (TARDEC) Warren, Michigan. This mutually-beneficial collaborative research investigation was accomplished under the terms of a Statement of Work (SOW) entitled: "Ice/Frost Detection and Evaluation" jointly signed in March 2004 by Ronald Phelps of NASA-KSC's Shuttle Processing Business Office, and Dr. Thomas Meitzler of TARDEC's Visual Perception Lab (VPL). Planning and implementation of the test procedures has involved collaboration between U.S. Army investigators from TARDEC and the US Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL), and NASA-KSC's ice debris team. This is the final report describing the most recent test procedures and results on the MacDonald Dettwiler Space and Advanced Robotics, Ltd. (MDA - formally known as MDR) of Canada ice detection system. This report completes the study documented in the initial survey report of available ice detection systems.[1]

Objectives

The primary objective during this phase of the joint research effort, completed in March 2005, was to test various operating features of MDA's current prototype ice detection system. The MDA system has been designed to remotely detect and quantitatively measure ice formed on the Spray-on Foam Insulation (SOFI) surface of the External Tank (ET) of NASA's Space Shuttle during pre-launch operations. The formation of ice (and frost) is a common occurrence on the insulated ET containing cryogenics – in this case super cold liquid hydrogen and liquid oxygen. The reason ice is of critical concern is the possibility of it breaking off the ET during liftoff and vehicle assent, and subsequently striking and possibly damaging the orbiter crew compartment windows, Reinforced Carbon-Carbon (RCC) panels, or thermal protection tiles, thus placing the crew and vehicle at risk.

Description and Physical Principles of the MDA System

The MDA device (shown in Figure 1 below) uses a Xenon strobe, a focal plane sensor array and filter wheel to collect successive images over several sub-bands, and then uses a computed ratio of the reflected intensities from the sample to determine whether or not ice is present. The Xenon near infrared wavelength strobe is low power (<30 Watts), and is used to illuminate a surface on which there may be ice – in this case, ET SOFI. After illumination of the SOFI surface, electromagnetic energy is reflected back and focused on an IR (1.1 to 1.4 micron) sensor. The sensor (an un-cooled focal plane array) provides input to a linked on-board computer.

Based on the electromagnetic theory of reflection of light at the surface of a dielectric (ice in this case), the computer estimates ice thickness, if present. Various predetermined thickness ranges are color-coded (e.g., blue = 0.020-0.029 inch, green = 0.030-0.039 inch, yellow = 0.040-0.049 inch, red $\geq$0.050 inch)[10] to help the operator interpret quantitatively, the information displayed on the system monitor. A circular "bulls-eye" is shown on the system display for a target area. The average measured ice thickness from pixels located in the bulls-eye (64 pixels—8 x 8), is displayed on-screen in a field labeled "tkns in" (i.e. thickness inches). The system and its components (sensor, VHS recorder, and battery power supply) are contained in N_2 purged enclosures, and are mounted on a two-wheeled portable cart as shown in Figure 1 below.

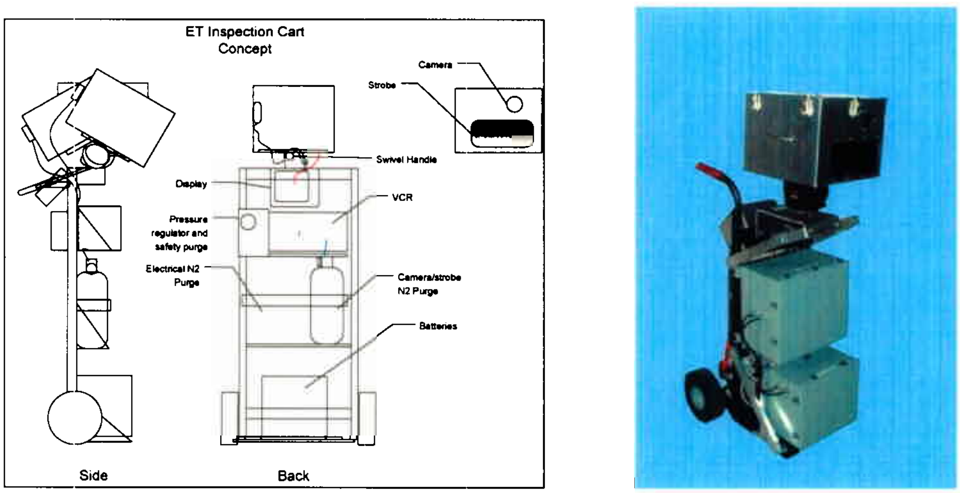

Figure 1: MDA ET Inspection System Cart

The MDA ice detection system operates on the physical principle discovered by the inventor, Dr. Dennis Gregoris[3], that there is a specific wavelength band over which the electromagnetic (EM) reflectance spectra of ice and water are significantly different. These bands are part of what is usually referred to as the near infrared or shortwave infrared (SWIR) part of the EM spectrum, between 1.1 and 1.4 microns.

Referring to Figure 2 below, as light is incident on a thin dielectric (e.g. ice), a fraction of the light is reflected at the air/dielectric interface, and the rest of the light is transmitted through the dielectric. The transmitted fraction propagates through the dielectric until it reflects off the substrate. The light reflected off the substrate returns through the dielectric until it reaches the dielectric/air interface, where it is again partially reflected into the dielectric and the air. Some absorption of the light occurs as it travels through the dielectric. The internal reflection continues until all the light is absorbed completely by the dielectric.[3]

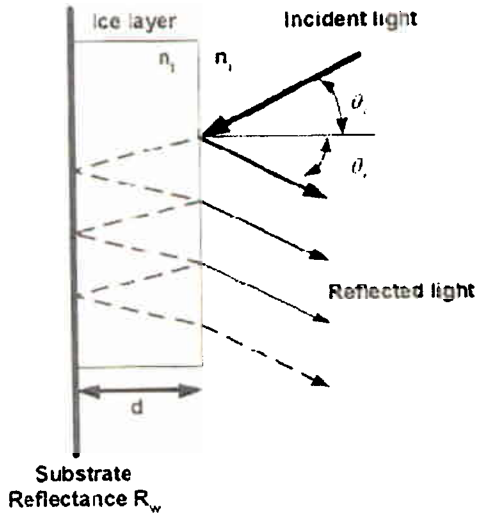

Figure 2: Reflection of light from a thin ice layer

For a dielectric of thickness *d*, the effective reflectance, $R_e(\lambda,\theta_i)$, of the dielectric layer is given by Equation 1 below,

$$R_e(\lambda,\theta_i) = R(\lambda,\theta_i) + \left[\frac{R_w(\lambda)\left(1-R(\lambda,\theta_i)\right)^2 e^{-2a(\lambda)d}}{1-\left(R_w(\lambda)R(\lambda,\theta_i)\right)^2 e^{-2a(\lambda)d}}\right], \quad (1)$$

where,

$R_e(\lambda,\theta_i)$ is the effective reflectance
$R(\lambda,\theta)$ is the dielectric spectral reflectance
$a(\lambda)$ is the spectral absorptivity
$R_w(\lambda)$ is the substrate spectral reflectance.

Using specific sub-bands within the near IR region of 1.1-1.4 microns, the spectral contrast is defined by,

$$C = \left[\frac{R_l - R_u}{R_l + R_u}\right], \quad (2)$$

where *l*, and *u* are the lower and upper bands respectively in Equation 2. Measurement of the reflected energy and the computation of the spectral contrast allows for the detection of ice on a surface and the estimation of the thickness *d*, of the ice on that surface. Below in Figure 3 (chart from U.S. Patent #5,500,530[3]), the reflectance is plotted versus wavelength for 0.5 mm ice and water layers with light incident normal to the surface. It is clear from Figure 3 that the IR reflectance of water and ice is very different and linear over a long range.

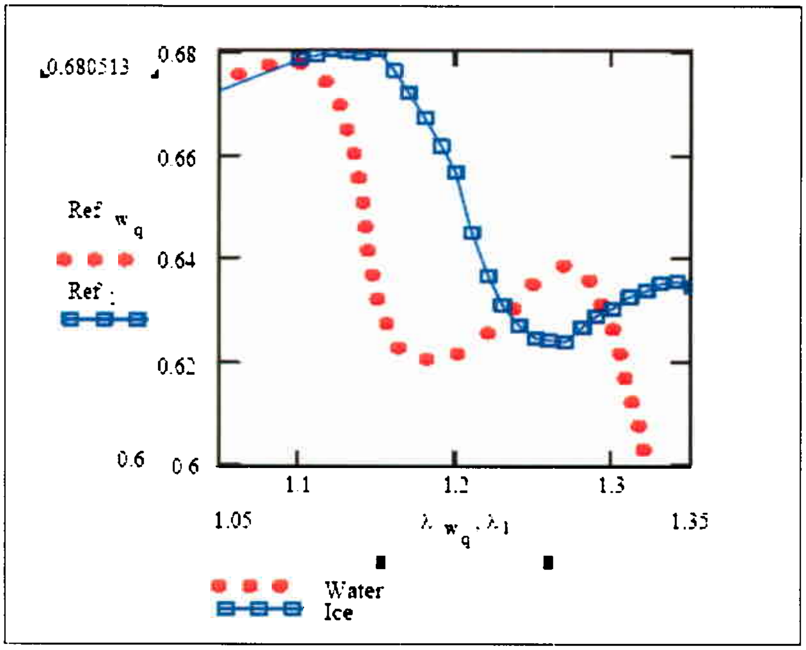

Figure 3: Computed spectral reflectance of ice and water versus wavelength[3]

The MDA system utilizes the following algorithm for estimating ice thickness *d*:

$$d = K_1 * \arcsin (C / K_2),^{11} \tag{3}$$

where, K_1 and K_2 are curve fit parameters, and C is the spectral contrast from Equation 2 above.

(For calculations showing the optical resolution and number of pixels as a function of range for the MDA system see Appendix B.)

General Experimental Procedure and Sample Preparation

The SOFI samples provided to TARDEC from NASA were used to test the MDA system. Some samples were used previously for the 2004 tests, and some were new or modified. Samples were labeled for identification and "up" orientation with a permanent marker as in earlier tests. Similar to last year's tests, ice was applied to the samples by laying them foam side down into Teflon coated baking pans. Inverting the samples in the water in pans produced a uniform ice surface that was flat and regular, and the Teflon surface provided easy sample removal. As mentioned in the NASA 2004 test report[1], besides making a smooth regular surface, this method of inverting the SOFI in a pan provided a way to more accurately measure the ice thickness. Since the backs of the samples were void of ice, thickness could be measured before and after ice formation, and therefore the ice thickness was the difference between measurements. Ice samples were made in the freezer by placing weights (rocks and plastic containers of ice) on top of the samples to prevent them from floating, and water was added to a desired height. Since some samples were milled flat or in steps with only 1/32 inch face clearance, air bubbles were dispersed from under

the samples by lifting one side out of the water, and then slowly lowering it back into the water, thereby forming a wedge to drive out bubbles.

For imaging with the MDA system, the SOFI samples were placed on a plywood board and easel (except for Goal 2 – see below). The board and associated metal brackets were painted black to reduce any background noise. Hooks were attached to some samples for hanging on the board, and a 1-5/8 inch ledge at the bottom of the board held others up. Large samples were set on the ledge and attached to the top with flexible metal straps. Since the MDA camera works in the IR, normally visible labels were invisible. Plastic refrigerator magnet numbers/letters were hung near each sample as they were imaged for identification later in the video recording.

MDA camera data was taken of specific areas of each sample corresponding to similar areas where ice thickness had been (or would be later) measured with the dial gauge (e.g. corners, center, and stepped areas). In all tests the MDA onboard VCR was used to record the imagery. In later tests, the audio output from the camcorder was input to the audio input on the MDA onboard VCR for simultaneous audio (e.g. voice) recording to provide additional information during the tests.

The original plan was to use an environmental chamber located at the TARDEC test site that would allow precise humidity and temperature control However, malfunctions of that facility required a revision in plans. There was a possibility of using the environmental chamber at Ford Motor Company's Science Labs, but that would have entailed a lot of movement of the ice detection system, which would have caused numerous complications. It was finally decided to take advantage of the cold weather that occurs during the winter in Michigan. With the arrival of the MDA system, tests were conducted from February 22 - March 17, 2005.

Manual Ice Thickness Measurements

A Westward dial indicator gauge (range: 0 to 1 inch x 0.001 inch, accuracy: ± 0.002 inch) with magnetic base and extension rods was used to measure ice thickness on the SOFI samples. Readout was from an analog dial display to 0.001 inch. The reading was "zeroed" by a spring adjustment rod. Since it only had one inch of range, an optics quality 1 x 2 x 3 inch calibration block, and if needed, a precision cut ¼ inch Aluminum plate, were used to adjust the zero position with the spring rod. Since the dial gauge probe had a consistent spring tension, the applied contact force was consistent, and therefore so were the measurements. To reduce ice melting, the metal dial gauge probe tip was covered with a plastic (screw thread) cover and Kapton tape. This configuration probe tip measured about ¼ inch in diameter. (Kapton tape was recommended by the MDA engineers as a very good insulating material.) A larger Styrofoam probe (2 x 1.5 x 0.5 inches thick) was also used for Goal 1 tests to measure an average surface area height of frost, and to spread the measuring force over a larger area to help keep from deforming the frost.

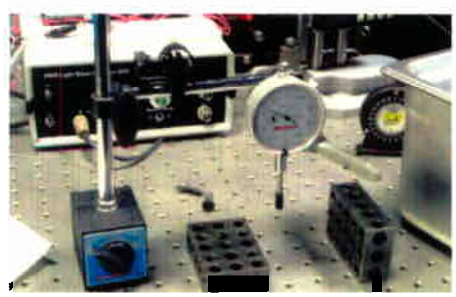

Figure 4: Dial gauge & calibration blocks

Samples were measured for height to calculate ice thickness for Goals 1, 3, and 4. For Goal 1, the dial gauge was set to measure horizontally against the SOFI sample attached to the side of the liquid Nitrogen (LN2) container. A steel L-shaped corner brace was bolted to the optical table to be used as a template to reposition the dial gauge base. The gauge was "zeroed" in the template after LN2 was poured into the container, but before ice started accumulating. Later, after ice was formed, ice thickness was measured by repositioning the gauge base in the template. The variability in repeatability of measurements was found to be about ± 0.005 inch with the dial gauge – therefore, a cumulative accuracy of about ± 0.007 inch was estimated.

For Goal 3, samples were measured by laying them back-side down onto an optics table or calibration blocks. The very large samples (2B and 3B) had irregularly shaped foam back surfaces. To prevent rocking, a weight greater than 6 lbs, was set on top of the sample, in the center, to stabilize it during the measurement. A pad of Styrofoam was placed on the sample first, to isolate the ice from the metal weight, and to spread out the force. This Styrofoam base was also used when there was no ice. The weight was removed when measuring the center region, but there was assumed to be no rocking present when the probe spring force was applied to the center (this may not have been a satisfactory solution—see Goal 4 conclusions below). The dial gauge was "zeroed" and then several heights were recorded at semi-random positions (as chosen by the experimenter). Ice samples were quickly measured by gliding the probe over the surface and recording a range of heights in the specified regions. For coarse and milled un-iced samples, five semi-random measurements were taken in each corner and the center, except for the stepped samples, for which was recorded three points on each step (e.g. left, center, and right). The measurements were done with and without ice so that the ice thickness was the difference of the two measurements. During MDA scans, samples were usually measured before and after the MDA measurements to quantify any ice loss that may have occurred. As mentioned previously, the natural coarseness of the SOFI surfaces is quite irregular, approaching 1/8 inch to about 3/16 inch of depth between peak and valley, therefore it was difficult to accurately measure these samples, and for that reason these measurements should be considered approximations.

Goal 1: Determine if the MDA system can detect low-density ice (LDI), and if so, how it compares with the results for normal density ice (NDI).

Given:
According to information provided by NASA, the density of the ice buildup on the ET SOFI at KSC is in the range of 18-37 lb/ft^3.[2] Typical ice formation (as in a freezer) is normally about 57 lb/ft^3 and is not normally formed on the ET during KSC pre-launch operations. The reason for lower density ice at KSC has not been determined. However, ice is known to form from condensing water droplets out of the air onto the colder ET surface. It's also known that condensing water from higher areas of ET acreage trickle down to frost covered areas and freeze as ice. The combination of frost and ice may add in such a way as to give a lower density ice.

Determine:
The MDA tests done last year used: a) ice formed in a freezer (which is denoted as NDI – about 57 lb/ft^3), and b) captured snow – about 52 lb/ft^3. However, ice that has formed on acreage of the

ET at NASA-KSC has typically been in the range 18-37 lb/ft^3 (which will be denoted as low-density ice - LDI) This goal would verify how the MDA system responds to LDI.

In addition to the difficulty of forming LDI for the experiments, the difficulty of measuring ice density (weight/volume) needed to be solved – specifically the measurement of volume. Various methods have been tried with limited success[1]; but the method used in these tests is explained below. It should be noted, the idea that was described in the test plan for measuring density; by collecting the melting ice into a small beaker, did not work because the ice sublimated rather than melted, in the dry 21% humidity conditions of the laboratory.

Assumptions:

1. As defined by NASA KSC, typical ice as formed on the ET is in the density range 18-37 lb/ft^3 (KSC condition). Ice with density <18 lb/ft^3 (frost) does not pose a threat to the LCC.
2. LDI will grow on a thin section of LN2 cooled ET foam sample under room or modeled humidity conditions in a reasonable amount of time. This will simulate ice growth that occurs as on the full scale ET foam after the cryogenic propellants (LO2 and LH2) have been added.
3. A restaurant style stainless steel steam table pan with lid can be used as the LN2 container to which a thin section of ET foam sample will be affixed (using clamps, bands, or glue). The steam table pan is made of stainless steel, with no welds (except in the lid), of stamped construction, and therefore should handle the LN2 well. It also comes in various sizes with flat sides that will accommodate attaching the foam sample.
4. To more easily measure ice volume for density calculations a smaller cut smooth section of SOFI will be affixed to the container. It is assumed that this small smooth sample will form the same type of ice as the course sample on the front of the container. This assumption will be made due to the difficulty in accurately measuring the ice volume on the course (natural) SOFI sample.

Experimental Procedure:

For these tests, liquid Nitrogen (LN2) was used to cool a stainless steel container. LN2 has a boiling point (-321°F) – close to liquid Oxygen (-297°F), although not as cold as liquid Hydrogen (-423°F). The latter two being the oxidizer and fuel stored in the Shuttle's ET, respectively. A steam table pan (or chafing pan – denoted size: "sixth pan" – 5.5 x 5 x 5.75 inches – made of 22-24 gauge 18/8 stainless steel) with a slotted cover was used as an LN2 container. The container was snug fit into a Styrofoam block base with Styrofoam walls on two sides of the tank and a removable Styrofoam cover on top. As can be seen in Figure 5 below, a thin (approximately 3/16 inch thick x 4.25 inch x 3.75 inch) cut down sample (cut laterally) of course (natural) surface SOFI was attached to the front of the stainless steel container, and a small 2 inch x 2 inch x 3/16 inch thick flat surface (or smooth) SOFI sample to the side of the container. The samples were made thin to encourage ice growth since the SOFI is such a good insulator.

Figure 5: Thin SOFI samples attached to LN2 test container

The smooth 2 x 2 inch sample attached to the side of the container was used for ice density measurement. With a smooth flat surface, a more accurate measure of the average thickness of ice that would form on it could be measured. Since its surface area was known, an approximate volume of ice could be measured (density = mass/volume). It was assumed that the same type of ice would form on this smooth sample as on the natural SOFI sample mounted at the front of the container.

It was found after some attempts (using spray-on glue and contact cement) that two sided carpet tape worked best to attach the SOFI samples to the container. It adhered well during the LN2 exposure, did not warp the sample, and made it easier to remove from the container to weigh for the density calculation. After one or two uses, the tape degraded from the cold tests and was replaced.

The Styrofoam base with samples was clamped and locked down to an optics-grade table to maintain positioning for the dial gauge measurements. After many trials with mostly only frost and very low-density ice forming (<18 lb/ft^3), it was thought that higher humidity was needed. Since, the laboratory humidity was so low (21%), a cardboard box (measuring about 28 x 20 x 17 inches) with an open side (for viewing) was placed over the entire test apparatus to make an enclosed environment (see Figure 6 below). The inside of the box and the open side was sealed with plastic sheeting (6 mil) to form a water barrier to keep the humidity from wicking out through the cardboard and into the atmosphere. A small ultrasonic type humidifier was placed inside the box. These modifications finally proved to consistently yield a humidity of about 98%. Temperature and humidity data were measured inside the box with a digital Radio Shack temperature/humidity gauge (model 63-1030) with wireless probe.

Figure 6: Environmental chamber setup

A dial gauge was used for measuring ice thickness in these experiments but it needed to be pulled away from the sample to permit ice growth and be re-positioned later. A flat L-shaped corner brace was bolted to the optical table, which provided a fixed position template to position the dial gauge base for repeatable measurements. The dial gauge's magnetic base purports a 130 lb. holding force. A heavy weight (over 6 lb.) and bent metal strip clamps attached to metal guides bolted to the optical table were used to fix the Styrofoam base (with samples) to the table. Once everything was positioned and locked down it was found that the dial gauge could typically be repositioned in the L-brace and still show repeatable measurements of within about ± 0.005 inch. Westward, the maker of the dial gauge, states the accuracy as ± 0.002 inch, therefore a cumulative accuracy of ± 0.007 inch is estimated for dial gauge measurements.

LN2 was poured into the container in stepped increments to keep from shocking the glue that held the SOFI samples to the containers (the front sample actually popped off with some force at least once). After LN2 was added to the container, ice and frost accumulation typically occurred in about 15 minutes and continued to grow throughout the experiment (about 2-3 hours). The dial gauge was "zeroed" before ice began appearing. LN2 was added periodically throughout the test to replace what had evaporated.

It was brought up in conversations with Mr. Michael Ferrick of CRREL[7,8], who has been conducting ice research for many years, that condensing water from higher ET SOFI acreage was thought to trickle down to colder areas and then freeze (colder perhaps due to thinner SOFI or because of its proximity to a more exposed area – like Orbiter attachment points). This is believed to be, at least partially, the reason that the low-density ice (18-37 lb/ft^3) was found on the ET and not the very low-density ice/frost, (<11 lb/ft^3), that was seen in earlier laboratory tests. The combination of frost and ice may add in such a way to give a lower density ice measurement. Therefore, water was applied onto the SOFI samples periodically throughout the test so that it would freeze on the surface. At first this was done by trickling water down from a pipette, and later, by spraying water from a spray bottle directly at the samples. This finally proved to yield the "crunchy" ice mixed with frost (see Figure 7 below), and LDI densities in the desired range described by NASA (18-37 lb/ft^3)[2].

Once a fair amount of ice accumulated, the plastic sheathing over the front of the box was rolled back to permit a clear view to collect data with the MDA system. For these tests the MDA system distance ranged from about 16-25 feet away. Later the dial gauge was moved into position and the ice thickness was measured on the 2 x 2 inch SOFI sample attached to the side of the container. To give an average surface ice thickness, and to prevent melting the ice on contact, a small block of Styrofoam (2 x 1.5 x 0.5 inches) was placed over the small tip probe on the dial gauge, thereby providing a large insulated probe. The contact side of the Styrofoam was also covered with Kapton tape to provide an even better insulation barrier. Afterwards, the small 2 x 2 inch SOFI sample was removed from the metal container with tweezers and placed on a scale (Ohaus ARC-120 Adventurer electronic balance, 3100 g x .01g) to record the weight. The next day, when the SOFI was completely dry, the weight without ice and water was recorded. From this data the ice density (mass/volume) could then be calculated.

Figure 7: Close-up of frost/ice accumulation on SOFI samples and LN2 container

On the last LN2 test performed, to see if there was a difference of ice densities formed on the front SOFI sample compared to the small 2 x 2 inch sample on the side, the dial gauge was repositioned to measure the ice thickness from a high point (bump) on the front course (natural) surface sample. The ice thickness was measured again with the Styrofoam block probe, and then the large sample was removed from the container for weighing. The density was calculated to be higher with this method; however, since only one small area (bump) was measured, it may not accurately represent the ice thickness over the entire SOFI surface.

Results:

Representative density data from the LN2 tests is shown in Table 1 below. The upper section of the table shows measurements from the 2 x 2 inch flat (cut) sample, and the lower section of the table (darker grey) is from the natural SOFI (course) 5 x 5 inch sample. As can be seen from the data, LDI (density = 18-37 lb/ft^3) was acquired only twice of all the recorded tests (highlighted in red). By definition, the rest of the samples were low-density frost. The comments in the right column briefly describe the course of development of the experiments.

Table 1: Frost/ice density values (LDI highlighted in red)

Date	Temp (F)	Hum. %	Weight (g)			Volume		Density (lbs/cu ft.)	Comments
			Total	Foam	Ice	Thick-ness (in)	2x2" area (cu. in.)		
2/15	71	34	1.37	0.81	0.56	0.038	0.152	14.0	
2/17	59	53	1.45	0.81	0.64	0.055	0.220	11.0	Styrofoam probe, humidifier and box, slowly positioned probe, some sprayed water.
2/24	56	97	1.87	0.80	1.07	0.130	0.520	7.8	Plastic lining, fine mist water bottle.
2/25	56	98	2.60	0.80	1.80	0.100	0.400	17.1	
3/3	58	98	1.80	0.72	1.08	0.137	0.548	7.5	
3/9	53	98	5.30	0.72	4.58	0.225	0.900	19.3	Sprayed w/water frequently - sample developed good ice layer from spray, MDA showed central large red area, bordered by blue-green.
3/15	53	98	5.52	0.72	4.80	0.327	1.308	13.9	Sprayed w/water frequently, ice had large raised bumps which kept dial gauge from landing and so elevated thickness measurement.
							~5x5" area		
3/17	50-60	98	23.00	6.91	16.09	0.140	2.226	27.4	~5x5" course sample, measured high spot in approx. ctr. of sample w/small probe tip.
3/17	**50-60**	**98**	**23.00**	**6.91**	**16.09**	**0.360**	**5.725**	**10.7**	**~5x5", measured w/Styrofoam probe - light contact.**
3/17	**50-60**	**98**	**23.00**	**6.91**	**16.09**	**0.330**	**5.248**	**11.6**	**~5x5", measured w/Styrofoam probe - full contact.**

MDA system video of this test confirmed that the system does detect very low-density frost, as well as LDI, although with instability, that will be described later (see Goal 3). To compare LDI to NDI measurements it was thought that numerical comparisons could be made from later goal testing with NDI. Some limited side-by-side comparison of LDI to NDI was done outside the laboratory, however, the LDI/frost sample sublimated too quickly outside of its high humidity chamber, and so direct comparisons were not fruitful. It was observed that frost and LDI thickness was considerably underestimated by the MDA system, in comparison with actual physical measurements. For example, typical VPL testing ice accumulation data from March 17 showed frost/LDI thickness of 0.14-0.36 inches as measured with the dial gauge. Whereas, the MDA system measured values from 0.04-0.07 inches for this same sample and test (a 71-81% error). Evidence indicates also, that LDI measurements were underestimated in comparison to NDI measurements taken for Goals 3-4. Therefore, the MDA system was shown to be ice density dependent in its estimate of ice thickness. Thus, there would be considerable risk in relying on the MDA system solely for ice thickness estimation.

Goal 2: Determine if the MDA system can distinguish between ice and cold water on SOFI samples and whether water composition has any effect.

Given:
In the presence of ice and frost on the ET, water may also be present. Water and ice may be difficult to distinguish on the ET by an unaided eye. Tests should be performed to determine whether the MDA system could distinguish between ice and water. Since, the MDA camera is an IR based system, cold water near the freezing temperature should be used for testing. The

experimental setup should have samples of ice/water side by side so that the MDA system can image both in the same view simultaneously for easy comparison. For the MDA system to view water and ice simultaneously, from a horizontal placement, from the minimal test distance (about 20 feet), the samples would need to be viewed from their reflection in a mirror. (Energy in the infrared wavelength, which is sensed by the MDA camera, also reflects in mirrors.)

Last year's tests were only performed using local Detroit area tap water. The air at KSC may have other constituents that may contribute to variations in the ice formed on the ET. Other water sources should be tested to determine if the MDA system makes any unexpected discrepancies. Both water and ice made from differing water sources should be used. According to Michael Ferrick of CRREL, as ice forms any impurities in the water are separated out to the extremities of the ice (this is actually used as a water purification technique). The tests should confirm whether impurities in the water or on the surface of the ice may affect differentiation.

Determine:
Verify that the MDA system can discriminate between ice and water on SOFI samples, and using three different water sources (tap, distilled, and local rain), confirm that various impurities in the water and ice do not affect the index of refraction, η_{H2O} and hence, the accuracy of the MDA system's prediction of the presence of ice, regardless of its source.

Assumptions:

1. The sample pieces of SOFI and their surface textures are similar enough to be considered identical for all tests (in fact, it's believed that the small samples were all cut from the same large piece).
2. The MDA system-to-sample distance can be held constant.
3. The samples can be scanned within the same (temperature/humidity) environment for comparison.
4. For ease of formation, NDI type ice would be used (as made in the freezer) and this would suffice to model, for this test, the LDI type ice that occurs on the ET at KSC.
5. Ice density would be similar between all samples (i.e. the ice would be made in the same freezer).
6. The samples as viewed from their reflection in a mirror would not degrade the MDA detection appreciably.

Experimental Procedure:
Degradation in the reflected mirror signal was thought to be minimal, so a standard bathroom type mirror was procured. A platform was constructed to hold a 36 x 24 inch flat mirror, at about a 60° angle from the horizontal. All three sample types were imaged simultaneously to see differences more readily. Also, half of the sample would be covered with ice, and half with water, to see differences side-by-side. The ice/water would be ramped, to see any thickness detection problems.

Three SOFI samples were made with ramped ice thickness; thicker ice at the top, ramping halfway down the sample to zero thickness (see Figure 9 below). The samples were placed into

water trays in such a way to show a ramped thickness of water, from thinner to thicker. Only SOFI with coarse face was used for this test. The ramped ice was prepared on these samples by placing them face down into pans at an angle to the pan bottom (to form the ramp of ice), and with the pan bottom also tilted at another angle (with packing foam - to form the ice only at the top of the SOFI). As this was more of a qualitative test, angles were approximated by eye and sufficient to cause ice to be formed on approximately half the sample, and with the ice ramp going from about ¼ inch to 0 inches thickness. The samples were held at an angle in the pan until frozen by metal straps and hand clamps, and weights were used to keep them from floating. Three types of water (tap, distilled, and local rain) were used for the samples in the container and to make the ice.

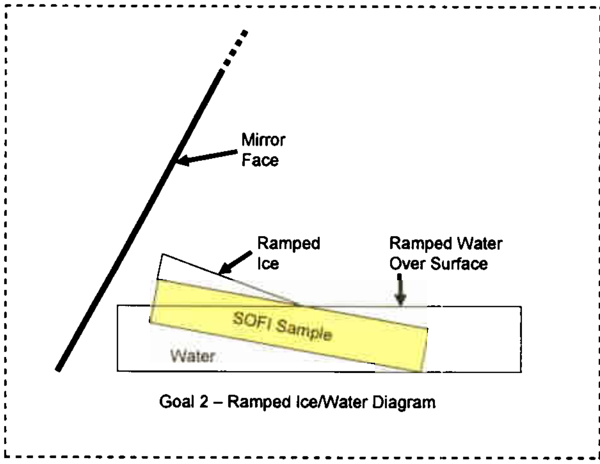

Figure 9: Schematic drawing of Goal 2

For MDA system scanning, the samples with ice were placed into plastic tubs, approximately half filled with the three water types, sufficient to have water about half way up the sample. The water had been kept in a 32-42°F refrigerator. Due to apparent refrigerator cycles, the temperature range accuracy was limited. The samples were held in the tubs at an angle with clamps and metal straps so that the iced half was held above water, and the bottom half was amply submerged. Samples were labeled "T", "D", and "R" pertaining to the water types: tap, distilled, and rain, respectively. Each sample was submerged in the same type of water as was used to make the ice (i.e. the sample with distilled water had ice that was made from distilled water, etc.).

All three samples were placed on a table with the mirror angled above them at about a 65° angle (from the horizontal) and imaged at the same time by the MDA camera from a range of about 20-25 feet away in the laboratory. The onboard VCR recorded the results. Sample water temperatures measured with the thermocouple probe during the test were about 47°F for all three types of water.

To help identify the ice/water border in the infrared MDA image, a piece of insulated wire was placed over the sample's ice/water border (see Figure 10 below). Thus, the wire served to define the ice/water interface border in the MDA infrared image. As can be seen in Figure 11 below, the

ice/water pseudo-colored border in the MDA image corresponded well with the wire's visible position in the MDA image. The areas in the tubs that have been pseudo-colored black (or "undefined") correspond to water, and the colored areas (mostly red) are ice.

Figure 10: Goal 2 mirror setup (note: wire ice/water border marker)

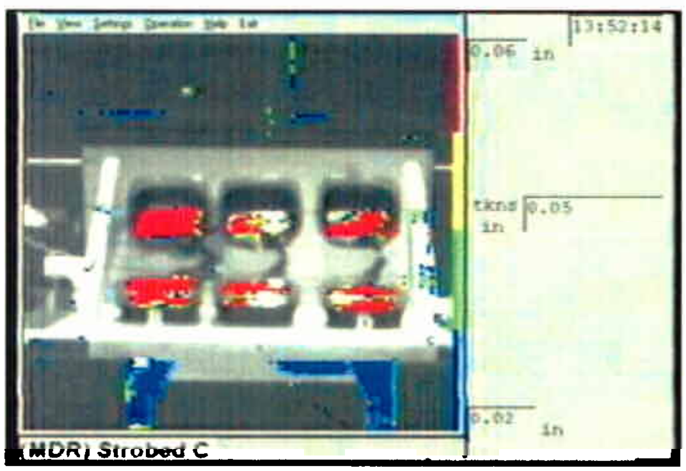

Figure 11: Goal 2 MDA image

Results:
It was evident from the MDA visual display that the system was able to determine the presence of ice on SOFI, regardless of the water composition, and could distinguish cold (47°F) water from ice on SOFI samples.

Due to the nature of these tests, only qualitative results (and not quantitative data) are presented to answer the Goal 2 objectives. Through visual inspection, the MDA system consistently distinguished between ice and cold water, independent of water source: distilled water, rain water, or tap water. From this qualitative testing, it can be concluded that the composition of test water from different sources did not play a role in detecting water or ice made from the three

water types. However, it should be pointed out, that the MDA system cannot discern water from other "undefined" materials (e.g. wood, metal), because it had been calibrated for SOFI ice detection only.

Goal 3: Determine if the MDA system can detect and measure the thickness of ice greater than or less than 0.0625 inch (1/16 inch), and whether the estimation of ice thickness is range independent.

Given:
The 0.0625 inch threshold LCC is important (as mentioned earlier) for a "go—no go" launch decision because of the danger of falling ice onto flight crew windows, orbiter thermal tiles, or Reinforced Carbon-Carbon (RCC) wing panels. Also, launch structure access and distances from ice forming ET areas vary, and for that reason, range independence is important. NASA-KSC's launch pad configuration and sensor mounts dictated about a 25 to 75 foot range for T-3 hour ice debris team examination.

The MDA system variability's pertaining to this goal include: a) an expanding sensor averaging area with increasing range, b) the reduction in intensity of Xenon strobe light with range, and c) the overall uncertainty of the system being ± 0.02 inch as stated by MDA.[9] Calculations of system resolution at various ranges can be found in Appendix B. Table 2 below shows pixel resolution for a one inch target at various ranges.

Table 2: No. pixels on one inch target

Distance	Object Size	# of pixels on target
25 ft.	1 inch	2.12
50 ft.	1 inch	1.77
75 ft.	1 inch	0.71
100 ft.	1 inch	0.53

Due to the need to measure at ranges greater than the dimensions of the laboratory (approx. 40 feet), tests would need to be performed outside the building. With concurrent on-going Goal 1 testing showing difficulty in forming LDI (see Goal 1 above), tests would be performed with NDI, as formed in the freezer. (Note: with post analysis of Goal 1 testing, the MDA system was shown to be ice density dependent in its estimate of ice thickness, and therefore these results with NDI are only exemplary, at best.) As discussed previously, dial gauge measurement accuracy is estimated to be ± 0.007 inch.

Determine:
Verify that the MDA system can measure ice thickness greater or less than the NASA-KSC LCC, and whether the system is range dependent in the necessary 25–75 foot range. It should be realized that the MDA system uses a Xenon strobe and has fixed optics for the sensor, therefore it would be expected to have some inherent signal-to-noise ratio fall-off at some range— yet to be proven.

Assumptions:

1. Outside conditions, including ambient light and temperature, would be reasonably constant for the duration of the tests to give valid results for comparison.
2. Since it is easier to make, NDI type ice would be used (as made in the freezer) and this would suffice to model, for this test, the LDI type ice that occurs on the ET SOFI at KSC.
3. NDI that is made the same way (in the same freezer) should provide a constant ice density among samples.
4. The constituents of water used to make ice will not effect the MDA ice estimation, therefore, local tap water may be used (validated by Goal 2 test results above).
5. Dial gauge measurements are a valid mechanical method for verifying the actual ice thickness to some degree of accuracy greater than the MDA system.

Experimental Procedure:

For this goal, 5 x 5 inch samples were milled into various steps to quantitatively resolve ice thickness. However, early in testing, it was realized that the milled steps in these samples were too small (approximately one inch wide) for the MDA system to resolve, even at the minimum range of 25 feet. (See Appendix B for pixel resolution calculations of the MDA system to better understand limiting factors).

At our request, NASA-KSC sent two large SOFI samples (approximately 36 x 16 inches), for subsequent TARDEC testing. However, attempts to form ice onto these samples by applying a tape border to contain water, and freezing in the Warren outside environment, were unsuccessful because of difficulty in getting a water-tight tape-to-SOFI seal. So to fit them in an existing TARDEC freezer, the samples were cut down to approximately 11 x 16 inches. Two samples (labeled 2B and 3B – "B" for big) were milled to create a 1/32 inch deep step (see drawing in Figure 12 below). A 1/32 inch deep milled surface was created on these samples because: a) formed ice thickness most likely would be in the range of discernment for the MDA system (0–1/16 inch), and b) data points in the large step could be resolved at longer ranges (≥25 feet).

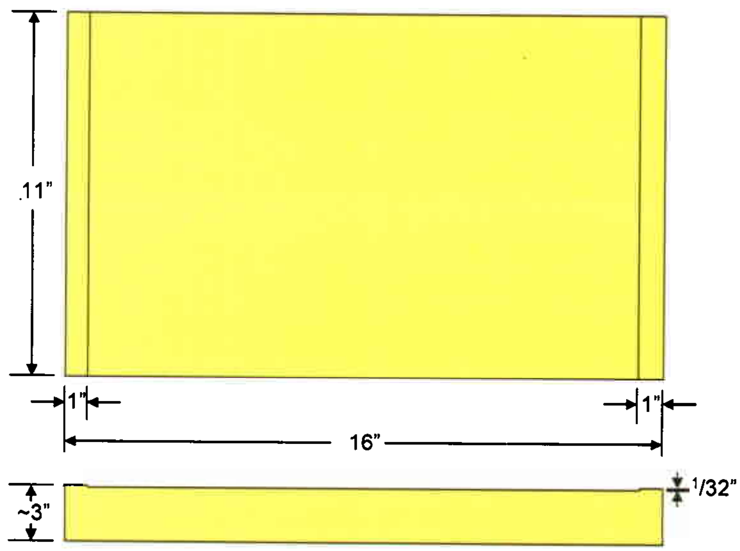

Figure 12: Diagram of SOFI milled 1/32 inch

Ice was formed on the large "B" samples by placing them face down (as described in last year's report[1]) into a Teflon coated cookie sheet or plastic/fiberglass cafeteria food tray. The cookie sheet was rigid, heavy-duty grade, and quite flat and not subject to warping. The cafeteria tray was also quite rigid. Samples with a shallow milled step (1/32 inch deep) could easily trap air bubbles in the step. To circumvent this, while one side of the sample was kept partially submerged in the water with a weight, the opposite side was lifted up and then very slowly submerged back down into the water. In this way a formed water wedge drove out the air as the sample was lowered, and this helped to produce more uniform ice.

Samples were mechanically measured before and after ice was formed with the precision Westward dial indicator gauge on an optical table to determine ice thickness. To keep from melting ice during a measurement, the dial gauge probe tip was covered with insulating plastic/rubber and Kapton tape. The large B samples proved to be difficult to measure with the dial gauge, because they did not sit flat on the table due to the irregular foam on the sample bottom surfaces. (In hindsight, these samples should have been milled flat on the bottom side as well.) To attempt to minimize this problem, a heavy weight (over 6 lb.) was set on top of the sample to keep it from rocking during measurements.

SOFI samples without ice were measured by picking five points semi-randomly in each region of interest. The regions measured were the four corners, and center. Semi-random, in the sense that, interesting high bumps and low points were usually measured in the region, and an attempt was made to get a uniformly spaced number of points in each region. For iced samples, instead of choosing five points, the dial gauge was slid over the ice in each region (i.e. corners and center), and minimum and maximum values were recorded. This was thought to more accurately represent the region since the ice was relatively flat and non-varying, and could be done faster, thereby minimizing melting. For

ease and speed of recording, one person usually wrote down the measurements while another calibrated, positioned, and read the dial gauge. The dial gauge was calibrated by re-zeroing on a calibration block (or blocks), usually before each sample was measured.

In some later tests, to quantify any ice thickness changes due to melting that may have occurred during testing, ice thickness was measured both before and after MDA scanning. Post analysis of this data showed ice losses in a few cases. In some instances it appeared there was an ice gain (not fully understandable). Due to the irregular results from these measurements, it appears that some measurement errors must have been made, most likely due to the irregular bottom surfaces of the large samples (as mentioned above).

For this test, the MDA system was placed outside the building at distances of 25, 50, 60, and 75 feet from the samples (see diagram in Figure 14 below). Sometimes testing started at the furthest test range (75 feet), and sometime at the nearest (25 feet), to rule-out any possible sampling side-effects. The Warren, MI outside temperature was sufficient to maintain the ice (except for one of the latest test days – March 15). For most of these tests the camera was moved, being more mobile, instead of the samples and easel. The MDA system's onboard VCR, and a standard camcorder and digital still camera were used to record the data. In later tests, the audio output from the camcorder was run through the audio input on the MDA VCR to record audio (e.g. voice information).

SOFI samples were placed on a plywood board, held up by an easel (see Figure 15). Hooks were attached to some samples for hanging on the board, and others were help up by the bottom ledge. The large samples were set on the ledge and held on from the top with flexible metal straps. Samples were labeled for imaging by hanging plastic number/letter magnets on the metal brackets attached to the board (these were visible to the MDA system).

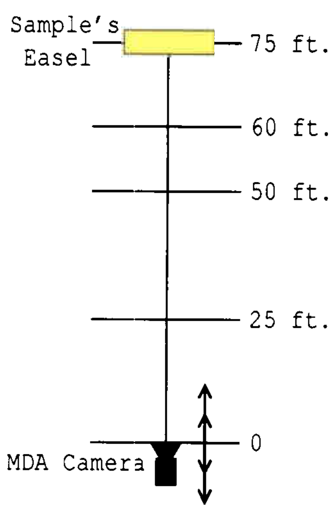

Figure 14: Schematic of the range test

Figure 15: (3/17/05) Iced 2B & 3B SOFI samples shown mounted on easel for measurement

The MDA system displays estimated ice thickness data in an on-screen field as calculated from an 8 x 8 array of pixels located within an on-screen "bulls-eye" circle. The large "B"

sample regions could be fairly well targeted at each range (see Figure 17 below). Noting the instability in the MDA system readings (discussed further below), it was decided to wait ten system refresh cycles (strobe cycles) to record ten bulls-eye measurements for each region of interest. The ten bulls-eye measurements were then recorded manually and averaged at a later time when watching the recorded video.

Results:
As mentioned above, the data taken for the large samples was most pertinent because of several reasons: a) for long range, the sensor field of view was too small to resolve the steps on the small 5 x 5 inch samples, b) operationally, the larger samples more closely resembled the actual ET SOFI acreage, and c) it appeared that the large samples of SOFI produced a more uniform response of the sensor, and less signal noise resulted in the displayed image.

Figure 16 below shows a picture (left) of the large samples on the easel from a side view pointing out the melted ice regions, which occurred on March 15, and a corresponding MDA scanned image of these samples (right). Notice that the MDA camera was able to identify some of the ice devoid areas shown as white to blue in the MDA image. Areas displayed in red are estimated by the MDA system as having ice ≥0.05 inch thick.

Figure 16: Photo (left) 2B & 3B milled samples with melting, corresponding MDA image (right)

Figure 17 below shows an MDA image of samples 2B and 3B, side by side, from a distance of 75 feet. Note, that the diameter of the bulls-eye target (white outlined circle on left-most sample) at this range encompasses over 70% of the height of the 16 inch samples.

Figure 17: Sample 2B & 3B (3-17-05) 75 foot range

Figure 18 below shows representative MDA ice thickness estimation data as a function of range for sample 3B. The compass directions: NW, NE, etc. denote upper left, upper right corners of the sample, respectively. Although, one would like to see a horizontal straight line for all ranges, indicating linearity and consistency of measurements, this was not observed. (See Appendix C for more charts showing data vs. range). As Appendix C shows, there was a significant lack of horizontal linearity in the various charts for large SOFI samples 2B and 3B during two winter test days. These plots indicate a lack of ice thickness measurement consistency as would be indicated by horizontal linearity as a function of range.

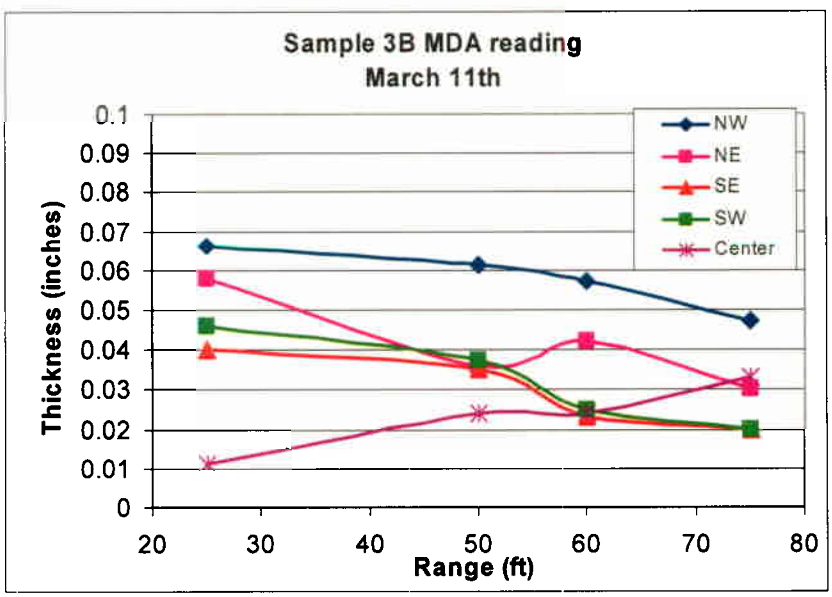

Figure 18: MDA system data for sample 3B on March 11th - measurements from close to far range

The gauge and measured MDA sensor values for ice thickness for SOFI samples differed appreciably. Irregular data from gauge measurements prompted a reexamination of

samples 2B and 3B, which is explained further in Goal 4 below. The origin of these errors is not certain, except to note again, that these B samples had irregular bottom surfaces, and therefore this may have made an unstable measuring platform.

The MDA system was found to be unstable during testing. MDA has stated that some of the noise or instability may be attributed to the long time delay between strobe flashes (three seconds), and spatial fluctuation of the strobe beam pattern, which are problems present in this proof-of-concept system. Figure 19 below shows a series of eight consecutive images (read left to right, row-wise) that were digitized after each strobe flash (every 3 seconds) from the MDA video tape for Goal 3 on March 17 at a range of 50 feet. This test was done outside and a large piece of cardboard was used as a background (behind the easel), as it was thought to reduce the background noise. Each picture is a consecutive (every three seconds) system measurement.

In the upper center of each image, ice can be seen in pseudo-color. The "bulls-eye" circle is in the approximate center of the left-most sample (2B), and the average reading from this circled area is shown in the right-center box labeled "tkns in" (i.e. thickness inches). A vertical color bar can be seen at the right edge of the picture, which shows the pseudo-color mapping from blue (0.02-0.03 inches), to green, to yellow, to red (>0.05 inches). Of note, is the instability of the pseudo-colored images, especially in the last two in the series. The instability can be seen in the readings given by the bulls-eye averaged field "tkns in" as well: 0.05, 0.05, 0.04, 0.05, 0.04, 0.04, 0.06, and 0.03, in sequence. Non-ice areas (e.g. parts of the cement driveway, and cardboard backdrop) are erroneously pseudo-colored in some images. However, it should be pointed out, that the MDA camera was only calibrated for examining the SOFI substrate, and as a result non-SOFI areas are undefined.

Empirical evidence indicates that the MDA system can detect ice less than or greater than 1/16 inch, however, with inconsistency. The system showed a lack of consistency in ice thickness measurements. The empirical evidence, at this time, indicates the MDA system is not able to accurately estimate ice thickness independent of range (i.e. as range changes, so do the thickness measurements).

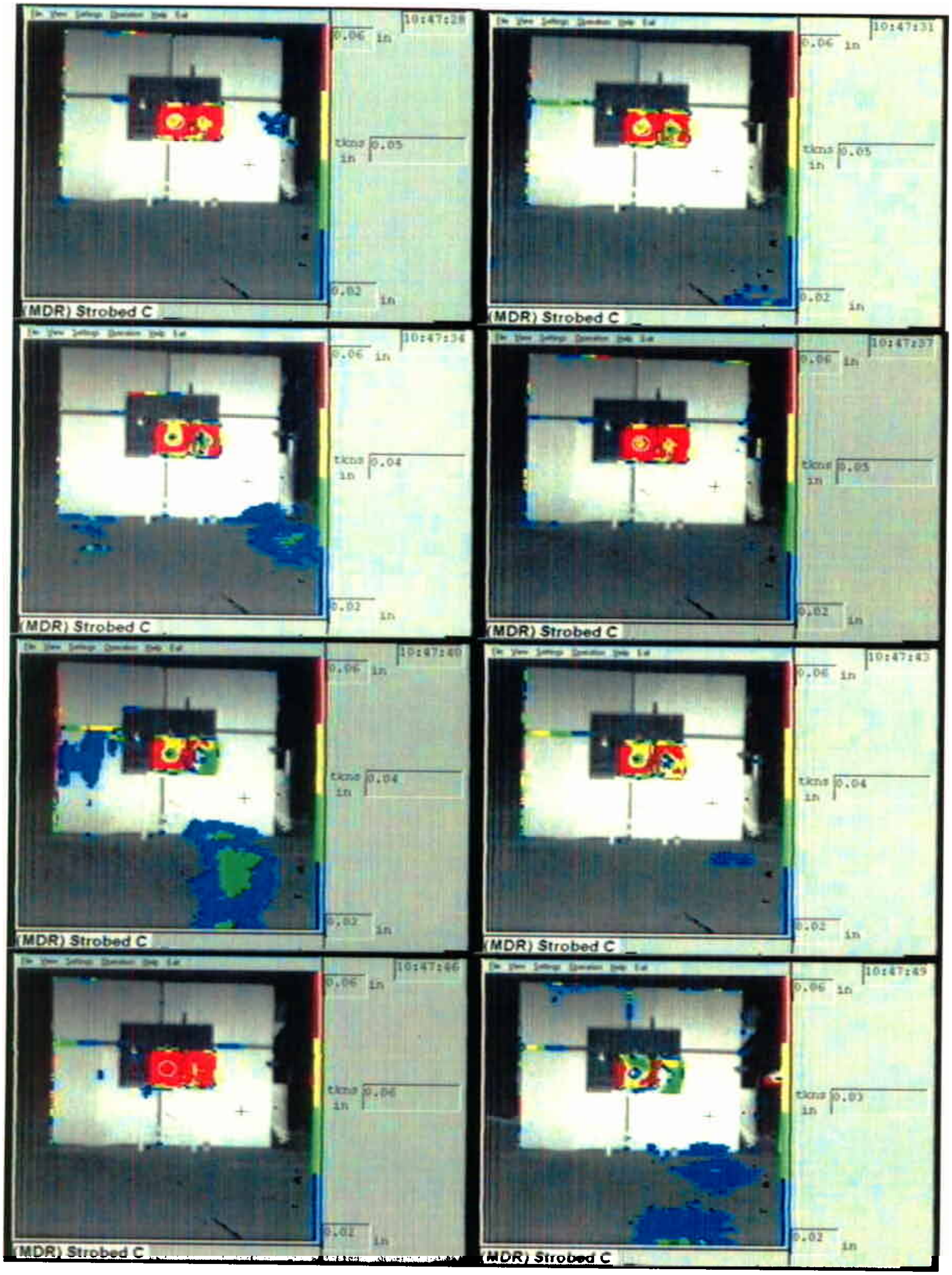

Figure 19: Goal 3 - range 50 ft. (3/17/05) MDA consecutive image series (read left to right, row-wise)

Goal 4: Determine the accuracy of the MDA system's ice thickness estimation.

Given:
Due to the similar nature of this goal and Goal 3, these tests were performed concurrently, and similar assumptions are identified. As in Goal 3, a dial indicator gauge was used to determine ice thickness. As mentioned previously, the accuracy of the dial gauge measurements is estimated to be ± 0.007 inch.

The MDA system variability's include: a) an expanding sensor averaging area with increasing range, b) the reduction in intensity of Xenon strobe light with range, and c) the overall uncertainty of the system being ± 0.02 inch as stated by MDA.[9]

Determine:
Verify MDA system results as compared to actual ice gauge measurements and determine ice thickness accuracy.

Assumptions:

1. Outside conditions, including ambient light and temperature, would be reasonably constant for the duration of the tests.
2. Since it is easier to make, NDI type ice would be used (as made in the freezer) and this would suffice to model, for this test, the LDI type ice that occurs on the ET at KSC.
3. NDI that is made the same way (in the same freezer), should provide a constant ice density of NDI type among samples.
4. The constituents of water used to make ice will not effect MDA ice measurements, therefore local tap water may be used (validated by Goal 2 testing results above).
5. Dial gauge measurements are a valid mechanical method for verifying the actual ice thickness to a degree of accuracy greater than the MDA system.

Experimental Procedure:
As this goal was done concurrently with Goal 3, the same samples and experimental procedures were used (see Goal 3 above).

Results:
The gauge and measured MDA sensor values for ice thickness for SOFI samples differed appreciably. Figures 20 and 21 below show average ice thickness measurements, with error bars, for the MDA system and dial gauge. Note, that although the large "B" samples were milled with a 1/32 inch (0.031 inch) step, the majority of ice measured thicker with the dial gauge. Various types of data analysis inconsistencies prompted a reexamination of dial gauge measurements made on SOFI samples 2B and 3B. When SOFI samples 2B and 3B were again measured in June 2005 (a few months after MDA testing), results were off about 0.03 inches (for sample 2B without ice), compared to the measurements made in March. Typical gauge measurements made on calibration blocks and other SOFI samples do not show this inconsistency (typically only ± 0.005 inch). The origin of these errors is

not certain, except to note again, that these B samples had irregular bottom surfaces, and therefore this may have made an unstable measuring platform.

As mentioned above, the MDA system did not have consistent readings even for fixed samples and distances. Inconsistency and inherent noise in the current proof-of-concept system, coupled with melting ice samples, and sample measurement difficulty for samples 2B and 3B, prevented a satisfactory data analysis. For these reasons, without additional testing, it is recommended that the current MDA system be used as a qualitative, rather than quantitative, ice measurement device to indicate the location and relative thickness of ice.

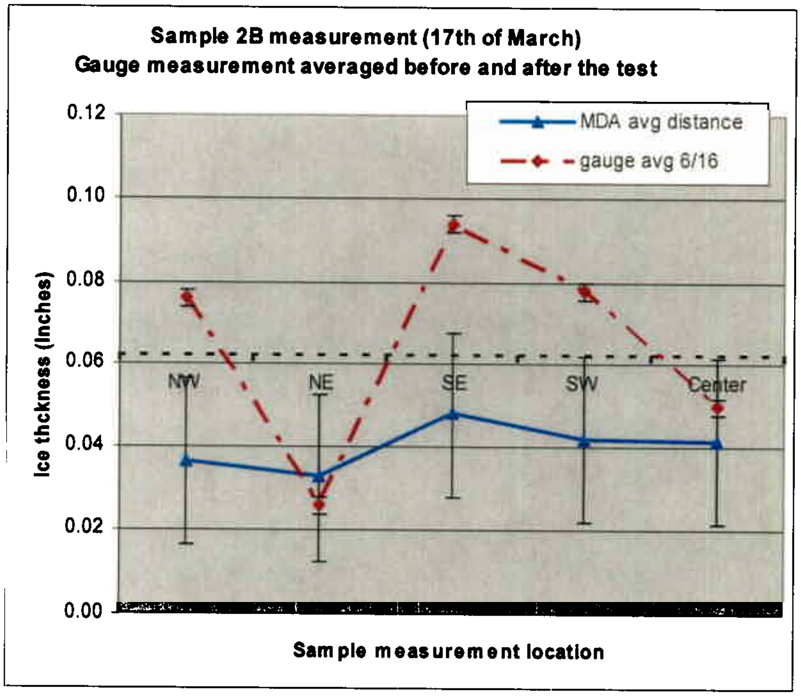

Figure 20: Sample 2B March 17

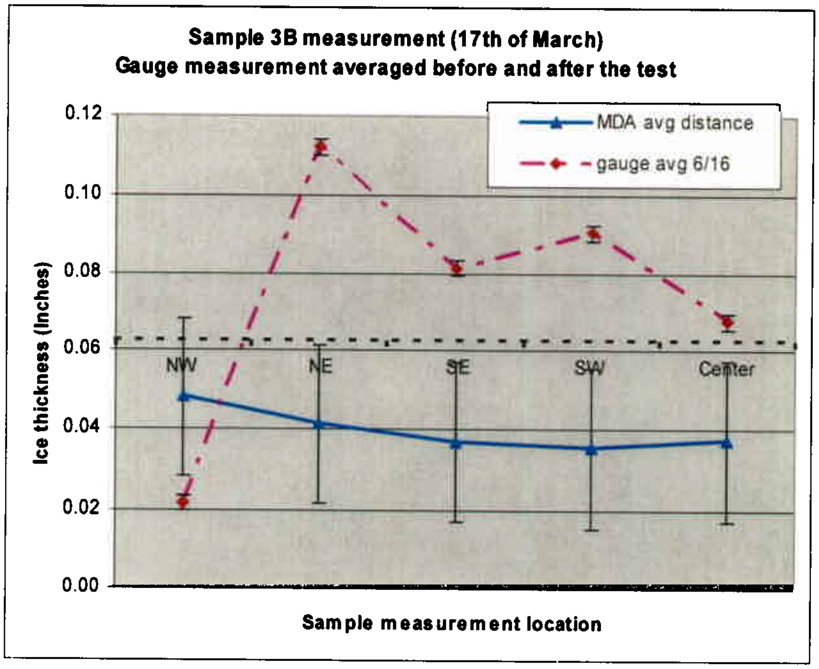

Figure 21: Sample 3B March 17

MDA System Improvements Made During Testing

1. At the request of TARDEC, MDA provided a software upgrade: a) to change the color of the bulls-eye screen cursor from black to white to improve viewability, and b) moved the bulls-eye averaging location vertically up to a "less-noisy" location.

2. Some foam packing material was attached to the front face of the VCR to prevent the VCR eject button from inadvertently being pressed when the pressurized door was bolted down.

Summary

MDA delivered the ice detection system to the TARDEC Visual Perception Lab (VPL) and various tests were done to validate the performance of the system. These tests were intended to replicate various parameters and conditions to which the system was designed to meet. Since there was only limited quality assurance testing of the MDA system by its developers before delivery to TARDEC, additional supporting data were not available for comparison and correlation purposes.

The ice detection system was integrated into a NASA approved and supplied cart (Figure 1) and fitted with a nitrogen pressurization system to meet KSC launch pad safety requirements. The TARDEC VPL checked the integrity of the nitrogen pressurization system and found it to lose pressure slowly, and is estimated to last 3-4 hours. (Electromagnetic emission tests were done prior to delivery at TARDEC and found to fall within EMI/EMC requirements.)

In summary, the four test goals are:

1. Does the MDA system detect low-density ice (LDI), and if so, how does it compare to normal density ice (NDI)? *The MDA system was found to be able to detect LDI and frost. The thickness of LDI was underestimated. The MDA system was shown to be ice density dependent in its estimate of ice thickness. That is, lower ice density seems to cause the MDA system to further underestimate ice thickness when compared to NDI. Thus, there would be risk associated with relying on the MDA system solely for quantitative ice thickness measurements.*
2. Can the system determine the presence of ice on SOFI irrespective of the water composition of the ice, and can it discern between ice and cold water? *The MDA system consistently distinguishes between ice and cold water, independent of whether the ice was made from distilled water, Michigan rain water, or tap water. Water composition was not seen to effect ice detection.*
3. Can the system detect and measure ice less than or greater than 1/16 inch, and is the estimation of ice thickness range independent? *Empirical testing indicates that the MDA system can identify ice less than or greater than 1/16 inch. However, the system showed a lack of consistency in ice thickness measurements. The empirical evidence, at this time, indicates the present proof-of concept MDA system is not able to accurately estimate ice thickness independent of range (i.e. as range changes, so do the thickness measurements).*
4. What is the accuracy of the system's ice thickness estimation? *Inconsistency, inherent noise, melting ice, and sample measurement problems prevented the acquisition of satisfactory test results. Without additional testing, after system modification, it is recommended that the current MDA system be used only qualitatively to detect the presence of water, frost, and ice, rather than quantitatively to measure ice thickness.*

Overall Conclusions

The present MDA system, as tested in the TARDEC VPL during the February 22 - March 17, 2005 test period is primarily a thin ice detection system that has the potential to qualitatively detect the presence on NASA ET SOFI of: a) low-density ice (18-37 lb/ft^3) common to the KSC launch environment, and b) ice of thickness $\geq$0.0625 inches thick (the NASA LCC). The system can clearly distinguish between areas of ET SOFI that are covered by cold water versus those areas that are covered with NDI-type ice, and where NDI is present to at least 0.02 inch thick. The system does not appear to be effected by water composition, either for detecting water, or detecting ice made from various compositions of water.

However, the present MDA system: a) does not consistently determine ice thickness for target areas in the range measured (25 to 75 feet), b) does not measure linearly in this range, and c) considerably underestimates low-density ice/frost thickness, as found on actual ET SOFI surfaces.

The system was also found to be unstable during TARDEC VPL testing. MDA has stated that some of the instability may have been due to the long time delay between strobe flashes and fluctuation in the strobe beam pattern, both of which MDA claims to have reduced with modifications in a subsequent prototype. The system has sensor range limitations, which are a function of strobe light intensity, sensor efficiency, and target surface reflectance and absorption. Whether, the physics inherent in the MDA system design is the limiting factor, or whether these issues may be resolved in subsequent engineering optics/sensor/software modifications, remains to be proven.

In summary, TARDEC investigators believe that the present proof-of-concept MDA device may be used by the NASA-KSC ice debris team for T-3 hour inspections to indicate areas where ice may be present on ET SOFI, and that may warrant further human inspection. At this stage of the MDA system's development, it is <u>not</u> recommended the system be relied on as the sole indicator of ice thickness, or ice presence.

Open Issues

There are several issues that need to be identified for report completeness. They are:

1. The present proof-of-concept MDA system should be modified to provide operational capabilities needed for reliable and accurate NASA T-3 hour ice detection and quantitative measurement. If developed, additional TARDEC testing should occur sometime between the first and second Return to Flight missions. And if so:
    a. Should future testing revisit the issue of ice with some salt and impurity content to create test samples that may be more representative of the KSC launch complex environment?
    b. Is there an accuracy issue that needs to be measured due to interference from the ambient launch pad lighting with the MDA system Xenon strobe?
    c. Should testing on the additional requirements for high incidence angle detection (70° to surface normal), and ranges to 125 feet be included?
    d. Should future testing emphasize utilizing LDI as formed on a scale-model ET tank?
    e. Should additional testing be done on-site at NASA-KSC to cover real environment issues?
2. Should investigation continue into alternative systems for ice detection and measurement (such as a low power laser system)?

Future MDA Work

TARDEC investigators suggest that more extensive tests be done on the current prototype system, or a successor, to determine precision and accuracy in estimating ice thickness under environmental conditions similar to the launch pad. MDA has expressed interest in pursuing development of an operational system that would meet the needs of the ice debris

inspection team. Future modifications that we can suggest to make the system more useful would include the following:

1. Greater stability and linearity in ice thickness estimates.
2. Ability to maneuver the bulls-eye in software (e.g. cursor).
3. Capability of imaging at closer and further distances (possible zoom).
4. Higher resolution focal plane array.
5. Digital data recording (disk, DVD).

Suggestions for Future NASA / TARDEC Collaborative Research

It is the desire of TARDEC VPL management and investigators to continue to collaborate with NASA-KSC and its ice debris detection team engineers to continue to support ice detection, measurement, testing and analysis of electro-optical systems for measuring ice thickness.

Consistent with the SAA, other areas of future collaboration could include:

1. Evaluation and improvement of the ice growth computer program SURFICE. Discussions with CRREL scientist, Michael Ferrick, expressed interest in working with NASA and TARDEC to increase the accuracy of the software by adding algorithms to account for surface irregularities of SOFI.
2. Investigation of the use of image fusion and 3D displays for assessing the condition of the Shuttle while in orbit, as well as the thermal tiles while in the Orbiter Processing Facility.
3. Use of vision models or image metrics to optically assess the amount of wear on Shuttle tiles.

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5. National Aeronautics and Space Administration (NASA). Lyndon B. Johnson Space Center. NSTS 08303- Space Shuttle Ice/Debris Inspection Criteria. 15 Sep. 1994.

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8. Ferrick, M.G., "Experimental analysis of icing conditions prior to launch of the shuttle Columbia," CRREL, March, 2003.

9. MDA Space Missions proprietary draft report for program: NASA Ice Camera Ice Detection Camera ATP, rev. dated 13 Feb. 2005.

10. MD Robotics Prototype Ice Detection Camera User Manual, Rev. 3.0, 6 January 2005, pg. 18.

11. Gregoris, Dennis, email correspondence to Dr. Thomas Meitzler, 16 June 2005.

Appendix A

Abbreviations

CRREL:	US Army Corps of Engineers' Cold Regions Research and Engineering Laboratory
ET:	External Tank
FOV:	Field of View
FSS:	Fixed Service Structure
HFOV:	Horizontal Field of View
IFOV:	Instantaneous Field of View
IR:	Infrared
LCC:	Launch Commit Criteria
LDI:	Low-density Ice (18-37 lb/ft^3)
LH2:	Liquid Hydrogen
LN2:	Liquid Nitrogen
LO2:	Liquid Oxygen
MDA:	MacDonald, Dettwiler and Associates Ltd.
NDI:	Normal Density Ice (~57 lb/ft^3)
RCC:	Reinforced Carbon-Carbon
SAA:	Space Act Agreement between NASA and TARDEC
SOFI:	Spray-on Foam Insulation
SOW:	Statement of Work
STS:	Space Transportation System
SWIR:	Shortwave infrared
TARDEC:	Tank Automotive Research, Development, and Engineering Center
VFOF:	Vertical Field of View
VPL:	Visual Perception Laboratory at TARDEC

Appendix B

Calculation of the Number of Pixels on Target by the MDA System

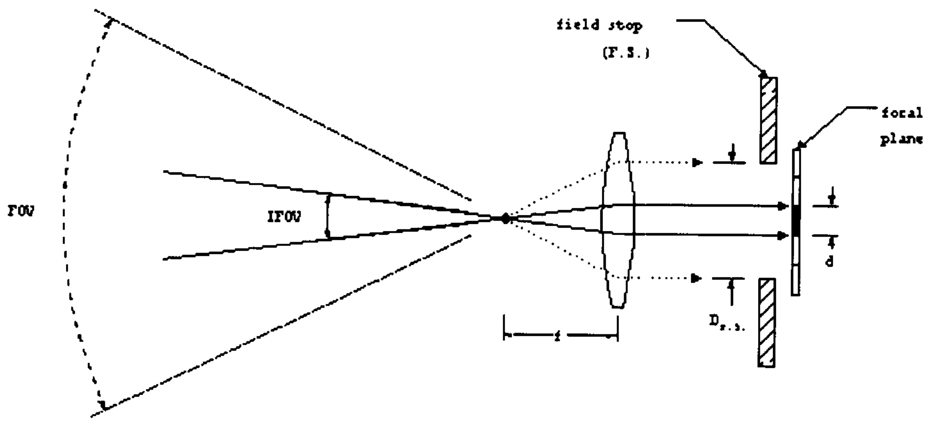

Figure B-1: Schematic of FOV elements used to define the spatial resolution

$$\mathrm{HFOV} = 2\tan^{-1}\left[\frac{(N_H - 1)d_{CCH} + d_H}{2f}\right] \qquad (1)$$

$$\mathrm{VFOV} = 2\tan^{-1}\left[\frac{(N_V - 1)d_{CCV} + d_V}{2f}\right] \qquad (2)$$

where:

HFOV, VFOV = Horizontal and Vertical Field of View respectively,

N_H, N_V = No. of horizontal and vertical detectors respectively,

d_{CCH}, d_{CCV} = detector pitch (center to center spacing),

f = focal length.

$$\mathrm{IFOV} = \mathrm{HFOV}/128 = \mathrm{VFOV}/128 \qquad (3)$$

$$\text{Height (one pixel at range R)}: \Delta h = R * \mathrm{IFOV} \qquad (4)$$

$$\text{Width (one pixel at range R)}: \Delta w = R * \mathrm{IFOV} \qquad (5)$$

The MDA system specifications include: a 128 x 128 focal plane array, each pixel is size 50 microns square, with a 60 micron pitch (pixel center to center), and a 38 mm focal length lens. The following table shows pixel resolution for a one-inch target at various ranges for the MDA system.

Table B-1: No. pixels on one inch target

Distance	Object Size	# of pixels on target
25 ft.	1 inch	2.12
50 ft.	1 inch	1.77
75 ft.	1 inch	0.71
100 ft.	1 inch	0.53

The following chart shows pixel resolution for a U.S. quarter at various ranges for the MDA system.

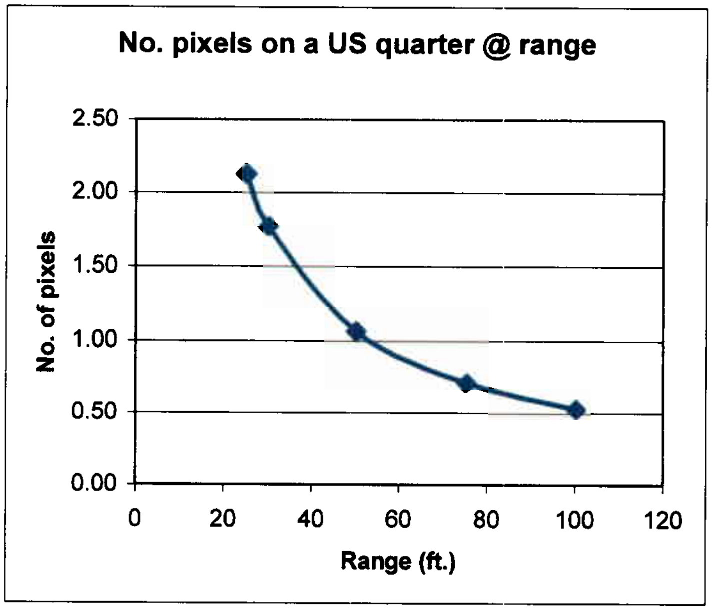

Figure B-2: Pixels vs. range for U. S. quarter sized target

Appendix C

Graphs of the Data Recorded vs. Range from the MDA System by Sample, Day

NW, NE, SE, and SW refer to the "compass direction" regions of the sample. E.g. NW is the top left corner, etc. It should be noted that March 15 was a warmer day and ice was observed melting during the test.

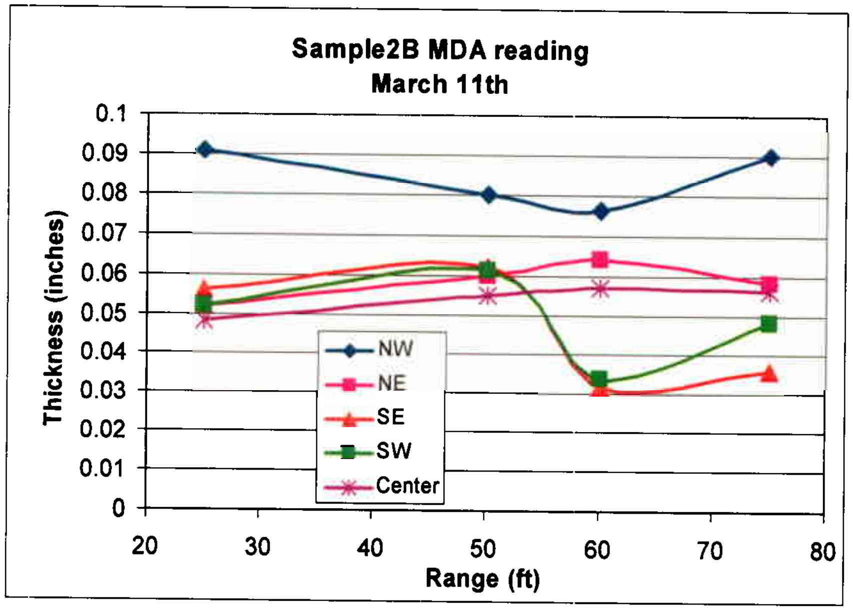

Figure C-1: MDA system data for sample 2B on March 11th - measurements from close to far range

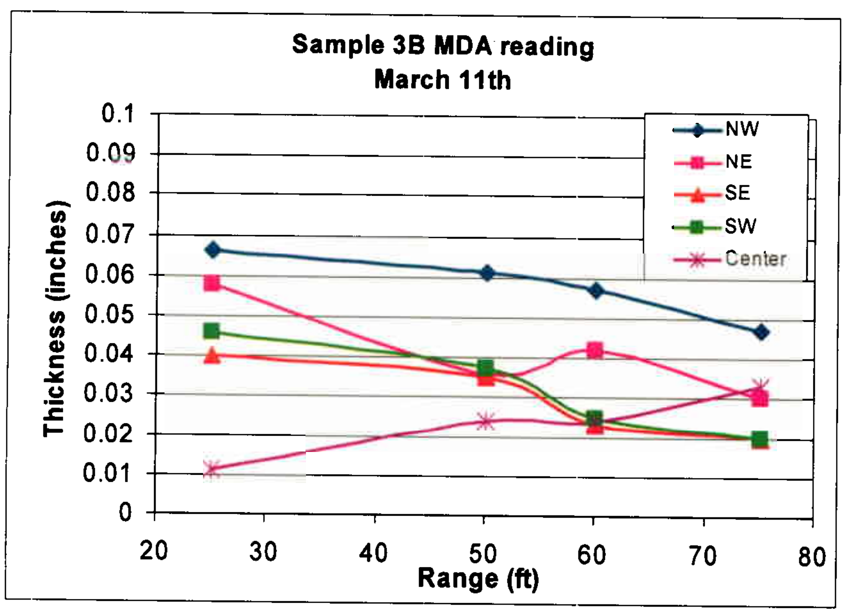

Figure C-2: MDA system data for sample 3B on March 11th measurements from close to far range

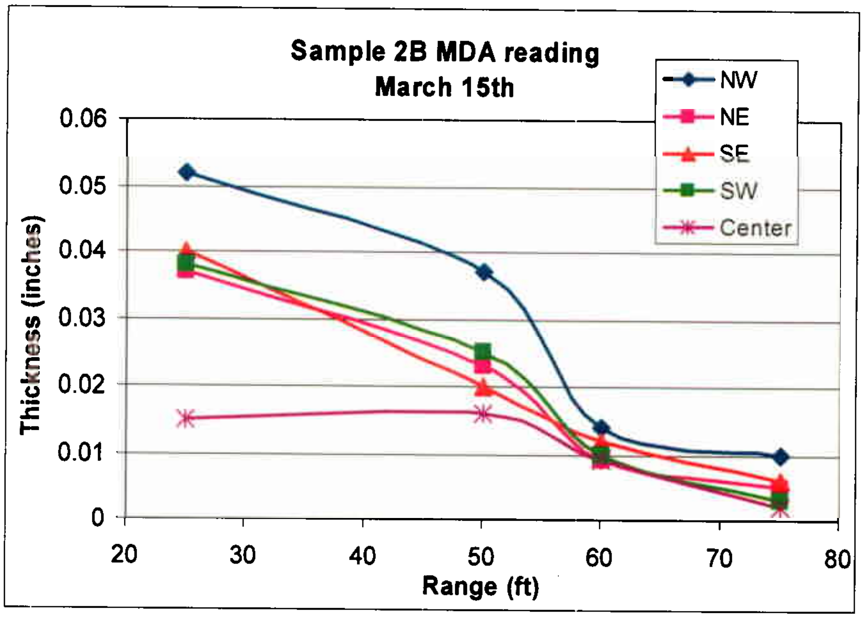

Figure C-3: MDA system data for sample 2B on March 15th measurements from close to far range

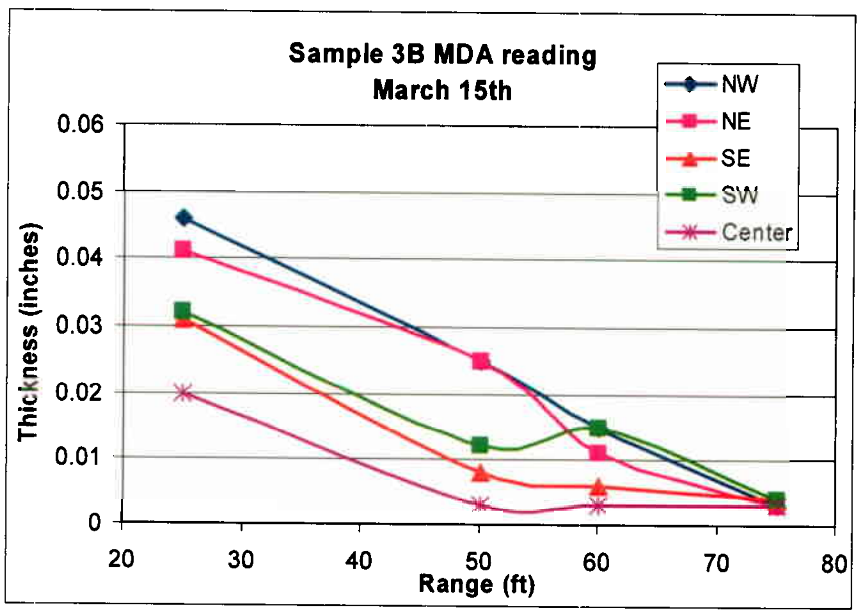

Figure C-4: MDA system data for sample 3B on March 15th measurements from close to far range

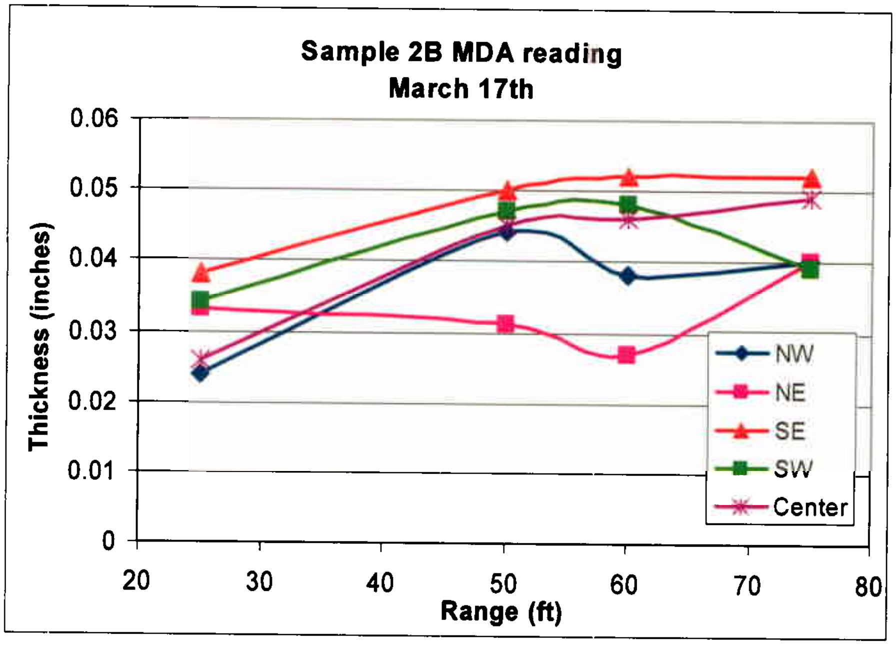

Figure C-5: MDA system data for sample 2B on March 17th measurements from far to close range

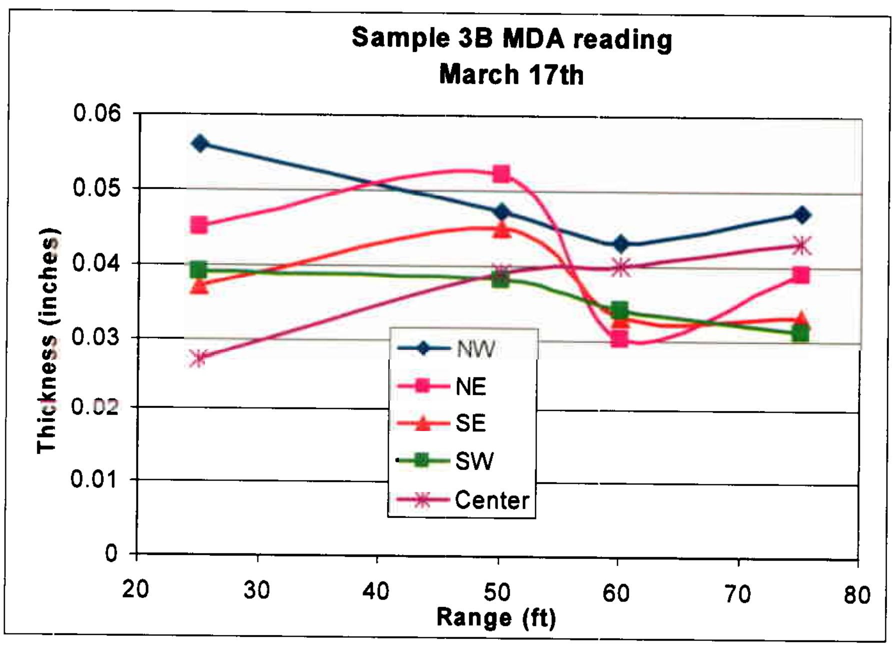

Figure C-6: MDA system data for sample 3B on March 17th measurements from far to close range